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HMPE FIBERS FOR OFFSHORE MOORING SYSTEMS: EXPERIMENTAL CREEP-RUPTURE AND LIFETIME PREDICTION MODELING

Daniel Magalhães da Cruz, daniel.cruz@ufrgs.br[1,2]
Marcelo de Ávila Barreto, marcelobarretobm@gmail.com[2,3]
Larissa Basei Zangalli, larissa@tecnofibers.com[2]
Carlos Eduardo Marcos Guilherme, carlosguilherme@furg.br[3]
Felipe Tempel Stumpf, felipe.stumpf@ufrgs.br[1]
Jakson Manfredini Vassoler, jmvassoler@ufrgs.br[1]

[1]Federal University of Rio Grande do Sul (UFRGS), Department of Mechanical Engineering (DEMEC), Applied Mechanics Group (GMAp), 90050-170, Porto Alegre/RS, Brazil
[2]Tecnofibers Desenvolvimento e Tecnologia LTDA, 88308-030, Itajaí/SC, Brazil
[3]Federal University of Rio Grande (FURG), Engineering School (EE), Stress Analysis Laboratory Policab, 96203-000, Rio Grande/RS, Brazil

Abstract: *Offshore mooring systems have evolved using high-performance polymeric fibers. This topic has led to the study and evolution of various polymeric fibers, the most promising being high modulus polyethylene (HMPE). HMPE fibers have low linear density and higher tensile strength than other fibers, resulting in greater linear toughness, demonstrating their strength and lightness. However, from a mechanical behavior standpoint, the challenge lies in creep, which literature suggests as the mechanism leading to the rupture of HMPE fibers. Aware of this fact, manufacturers have developed polymeric fibers with improved creep properties, named "Low Creep". This work aims to study the creep phenomenon in two HMPE fibers, one of which is designated as "Low Creep". We use creep rupture data for different loads and temperatures to mathematically model the creep life, predicting the possibility of offshore mooring systems made entirely of HMPE. Experiments were conducted at the POLICAB Stress Analysis Laboratory, Federal University of Rio Grande, Brazil. The tests are divided for each material into initial characterization: linear density, rupture (YBL), and linear toughness; and creep rupture tests. For creep tests, in addition to the two Chinese materials, 4 load conditions and 2 temperature conditions are used. For creep life prediction modeling, an existing literature-based model known as the Larson-Miller model, based on stress-time-temperature relationship, is utilized. These methods are based on experimental creep failure time and are adopted to calculate allowable stress and evaluate remaining life. These methods rely on the linearity of isotension results on a logarithmic time scale and the inverse of absolute temperature. In the experimental results findings, it is evident how the low creep fiber exhibits better mechanical behavior, and in the Larson-Miller modeling, expressions for creep time prediction for each fiber are obtained. The practical application lies in advancing creep determinations for HMPE, especially predicting the behavior of materials labeled as "Low Creep" for offshore mooring systems made entirely with HMPE, which would allow benefits such as longer life and lower installation costs, as well as less platform displacement.*

Keywords: *Synthetic Fibers, Experimental Characterization, Creep Behavior, Creep Life Modeling, Offshore Structures, Mooring Systems*

1. INTRODUCTION

The last few decades have witnessed remarkable advances in materials engineering, particularly in the domain of polymers, which have revolutionized several industrial sectors, including offshore engineering. Del Vecchio (1992) highlighted the transformative potential of polyester fiber ropes in mooring systems, marking a shift from traditional steel catenaries to more efficient Taut-Leg systems in synthetic fibers. This transition has enabled exploration in deeper waters, previously inaccessible with conventional materials due to their weight restrictions. The extensive use of polyester in offshore anchoring has been well documented in different studies (Dove *et al.*, 1997; Devlin *et al.*, 1999; Fulton *et al.*, 2002; Flory *et al.*, 2007; Al -Solihat and Nahon, 2015; Yang *et al.*, 2020; da Cruz *et al.*, 2023a).

This progression led to the exploration of alternative polymeric fibers for offshore applications, including polypropylene, polyamide, aramid and, notably, high modulus polyethylene (HMPE). Among these, HMPE has emerged

as a promising candidate due to its superior mechanical properties, including higher toughness, lower specific gravity and buoyancy in water. Studies have extensively investigated its potential in several offshore installations, such as Mobile Offshore Drilling Unit (MODU), Floating Offshore Wind Turbine (FOWT) and other permanent installations (Garrity and Fronzaglia, 2008; Vlasblom *et al.*, 2012a; Weller *et al.*, 2015; Lian *et al.*, 2017). However, the creep behavior of HMPE presents challenges compared to traditional materials such as polyester and polyamide (Lian *et al.*, 2015).

To improve the creep behavior of HMPE fibers, fibers designated as "low creep" were developed, and works can be found in the literature for such fibers (Leite and Boesten, 2011; da Cruz *et al.*, 2023b). Research efforts have focused on characterizing creep under different environmental conditions, load intensities, temperatures, creep life (Vlasblom and Bosman, 2006; da Costa Mattos and Chimisso, 2011; Lian *et al.*, 2018b; Bosman *et al.*, 2020; da Cruz *et al.*, 2022a). Although experimental studies involving large-scale mooring lines are ideal when targeting offshore mooring lines, they can be cost prohibitive. Thus, studying the behavior of HMPE multifilaments offers an economical alternative, given its correlation with the behavior of the rope, in addition to providing valuable insights into the behavior of the basic structure from which the mooring ropes are made.

This study aims to investigate the creep behavior of HMPE multifilaments under various load conditions and temperatures. The proposal is to use two HMPE fibers, one of which is designated as "low creep". The results are constructed with the creep-rupture for each material/load/temperature linkage. Furthermore, creep life modeling is proposed using the Larson-Miller Parameter (LMP), precisely to allow the equation and comparison of conventional HMPE fiber with low creep HMPE fiber. The results will contribute to improving understanding of the suitability of HMPE for offshore mooring applications, paving the way for better design and durability of mooring systems in deepwater installations such as Floating Production Units/Storage and Offloading (FPU/FPSO) and Marine Renewable Energy (MRE) systems, and a mooring system that can be made entirely in HMPE, allowing advancement deeper waters.

2. MATERIALS AND METHODS

2.1. Material Information

The study utilizes two synthetic fibers of high modulus polyethylene (HMPE) specifically designed for offshore applications, and Chinese manufacturing. Among the two fibers addressed in the study, one is designated as “low creep”. Coding and manufacturer information are not authorized, but Tab. 1 presents the mechanical characterization and properties of both fibers. The virgin spools are presented in Fig. 1.

Table 1. **Mechanical characterization of HMPE fibers.**

	HMPE	HMPE Low Creep
Linear Density [tex]	172.3	164.5
Yarn Break Load [N]	532.8	480.7
Strain at Break [%]	2.93	3.88
Linear Tenacity [N/tex]	3.09	2.92
Specific mass [g/cm³]	0.97	0.97
Stress [MPa]	2999.5	2834.5

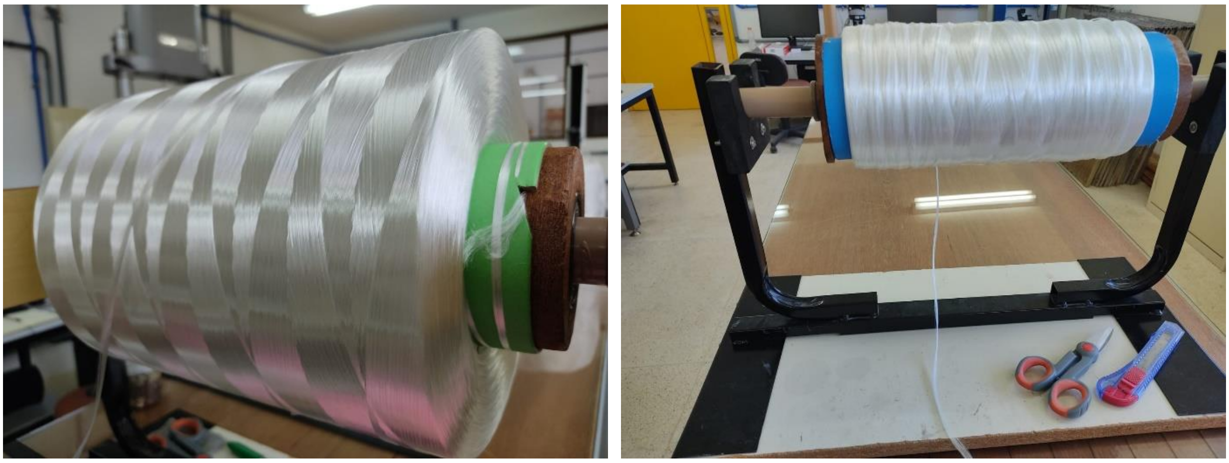


Figure 1. **Chinese multifilament spools, HMPE on the left and HMPE low creep on the right**

In accordance with ISO 18692-3 (2020), the fibers exhibit linear tenacity greater than 2.5 N/tex, thus qualifying as high-performance fibers. Additionally, due to the challenge of determining the area for stress calculation, it is emphasized that the values provided for tensile strength are obtained through Eq. (1), where the stress (σ) calculation is based on the breaking strength (F), linear density (ρ_L), and material density (ρ).

$$\sigma[MPa] = \frac{F[N] \times \rho[g/cm^3]}{\rho_L[g/m]} \tag{1}$$

2.2. Creep-Rupture Tests

The focus of this study is to investigate the creep behavior of HMPE fibers and compare it with "low creep" fibers. The creep test procedure is based on the recommendations of ISO 18692-3 (2020), which specifies test methods for high modulus polyethylene (HMPE) used in offshore stationkeeping. Before conducting creep tests, a visual inspection of the specimens extracted from the coil is carried out to avoid samples with excessive waves or broken filaments. Sampling consists of 5 specimens for each group.

Creep-rupture tests were conducted under specific conditions for 2 HMPE fibers (one of the fibers specified as Low Creep), 4 load conditions, and 2 temperatures. The temperatures used were 55°C (328.15K) and 85°C (358.15K). Loads are defined as a percentage of the breaking value (Yarn Break Load, YBL), with load levels at 50%, 60%, 70%, and 80% of the breaking strength. Reference Tab. 2 describes the loads as a function of the percentage of YBL, the force in Newtons, and the tension in megapascals.

Table 2. **Load levels for creep-rupture tests.**

Load Level	HMPE		HMPE Low Creep	
[% YBL]	[N]	[MPa]	[N]	[MPa]
50	266.4	1499.8	240.4	1417.3
60	319.7	1799.7	288.4	1700.7
70	373.0	2099.7	336.5	1984.2
80	426.2	2399.6	384.6	2267.6

The specimens used in the creep-rupture tests have a useful length of 200 mm (between grips) and are subjected to 60 rev/m, as recommended by the standard. The samples are gently ramped to the desired force level for creep at an evolution rate of 250 N/min. The equipment used is a universal testing machine equipped with a thermal chamber, Instron 5969, shown in Fig. 2. The results include time, extension, and deformation data acquired throughout the creep test until failure.

Figure 2. **Universal testing machine Instron 5969, overview on the left and thermal chamber detail on the right.**

2.3. Lifetime Prediction Modeling

One approach to model creep life is through stress-time-temperature linkage models to derive an expression for calculating permissible stress and assessing remaining life. Typically, these methods are based on experimental time-to-failure data for creep, among which the Larson-Miller method (Larson and Miller, 1952) is notable. Despite lacking mathematical robustness, the Larson-Miller model is highly effective in such modeling and is recurrent in the literature (Adamovich and Urzhumtsev, 1980; Kandare *et al.*, 2010; Morais Gautério *et al.* 2019; Amjadi and Fatemi, 2021).

The Larson-Miller employs an Arrhenius-type equation, as indicated in Eq. (2), where LMP is the Larson-Miller Parameter, T is the test temperature [K], C is a material parameter, and t_f is the total time to creep-rupture [h].

$$LMP = T \cdot \left[C + \log(t_f)\right] \quad (2)$$

The determination of parameter C is based on the linearity of isostress results on a plane defined by time on a logarithmic scale and the inverse of absolute temperature. Thus, its determination relies on data from at least two creep tests conducted at two temperature conditions within the same load group. Parameter C is the value where the fitted curve interpolates the y-axis of the logarithmic creep failure time (t_f).

3. RESULTS

3.1. Experimental Creep-Rupture Results

The experimental results of creep-rupture tests are presented in Tab. 3. It is observed that the low creep fibers exhibit significantly better performance in creep behavior, often maintaining proximity in rupture strain values compared to conventional HMPE fiber but with significantly longer times.

Table 3. **Creep-rupture results for time and strain failure.**

Fiber	Temperature	Load	Creep time [s]	Creep strain [%]	Rupture time [s]	Rupture strain [%]
HMPE	55°C	50%	955.81	20.284	1020.37	23.106
		60%	283.21	11.002	360.66	14.393
		70%	146.72	11.431	235.31	15.088
		80%	6.37	1.552	110.22	8.094
	85°C	50%	11.36	7.624	80.49	16.388
		60%	-	-	71.29	11.031
		70%	-	-	75.64	15.475
		80%	-	-	74.00	13.906
HMPE Low Creep	55°C	50%	9140.59	18.875	9197.93	22.048
		60%	3037.34	19.524	3105.91	23.371
		70%	497.56	10.313	579.22	14.749
		80%	128.30	2.761	222.32	7.459
	85°C	50%	422.43	17.422	479.58	21.092
		60%	112.62	14.907	181.72	19.669
		70%	11.74	4.259	92.99	11.423
		80%	-	-	87.19	10.415

To visualize the creep behavior over time (x-axis) and strain (y-axis), sets of curves separated by stress levels are proposed for each temperature, plotting both HMPE fibers for comparative analysis. Figure 3 presents the results for 55°C, where a noticeable gain in creep life for the low creep HMPE fiber is observed, with similar rupture strains among the different fibers under the same condition.

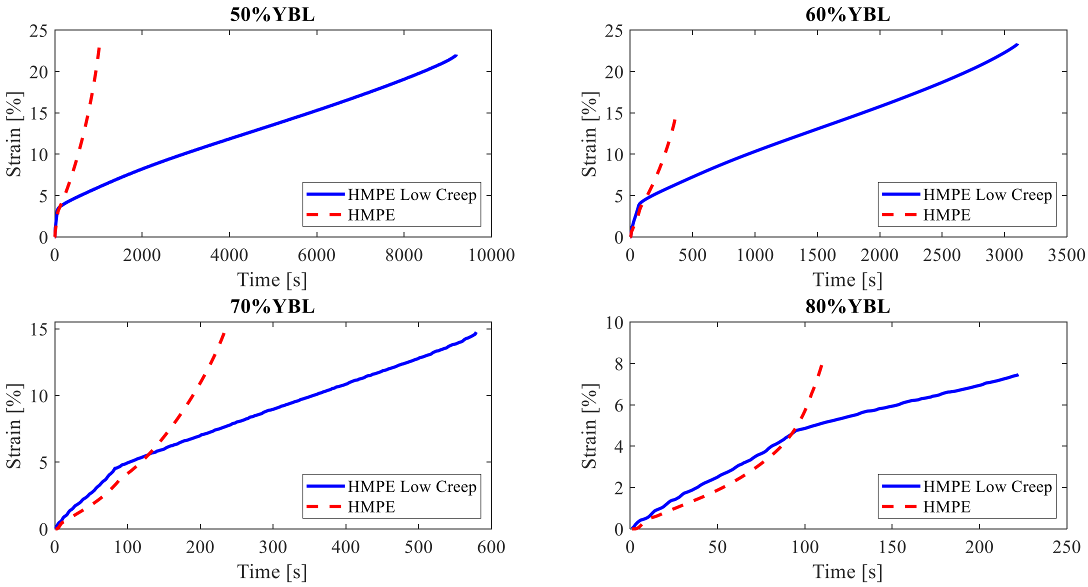


Figure 3. **Creep-rupture graphs, for 55°C.**

In Fig. 4, curves for 85°C are displayed. It should be noted, as indicated in Tab. 1, that some conditions did not reach creep (ruptured during the gentle ramp). Furthermore, it should be noted that higher temperatures combined with high loads cause the behaviors to converge (even though the low creep fiber exhibits a longer time to rupture). This is because thermal damage, combined with mechanical loading, causes the material to enhance chain mobility, resulting in excessive viscous behavior. Another way to interpret this is as an approximation of creep behavior as it approaches (or exceeds) physicochemical characteristics such as glass transition temperature and melting temperature. In this case, both fibers do not exhibit creep resistance because thermal degradation will deteriorate the material to the point where it no longer offers mechanical resistance.

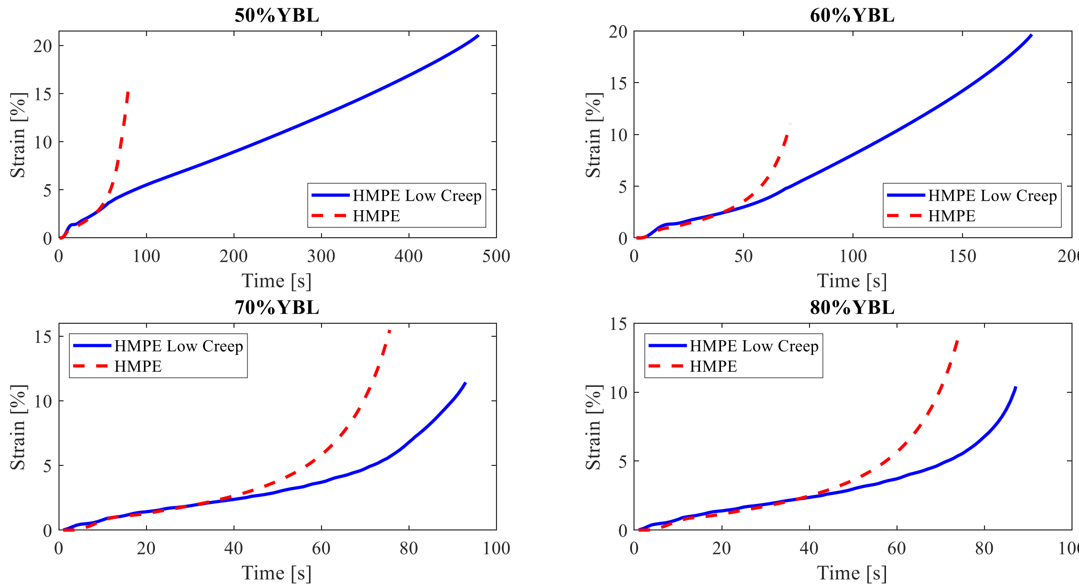


Figure 4. **Creep-rupture graphs, for 85°C.**

3.2. Creep Life Modeling Results

Following the Larson-Miller model for creep life modeling, the first step is determining the parameter C, which utilizes information on the failure time in hours and temperature in Kelvin. This involves constructing the graph described in Section 2.3, where discrete data points are for two temperature conditions (at least), and each linear fit curve is for a load condition that yields a parameter C. Figure 5 presents, on the left, the graphical construction for the HMPE fiber, and on the right, for the low creep HMPE fiber.

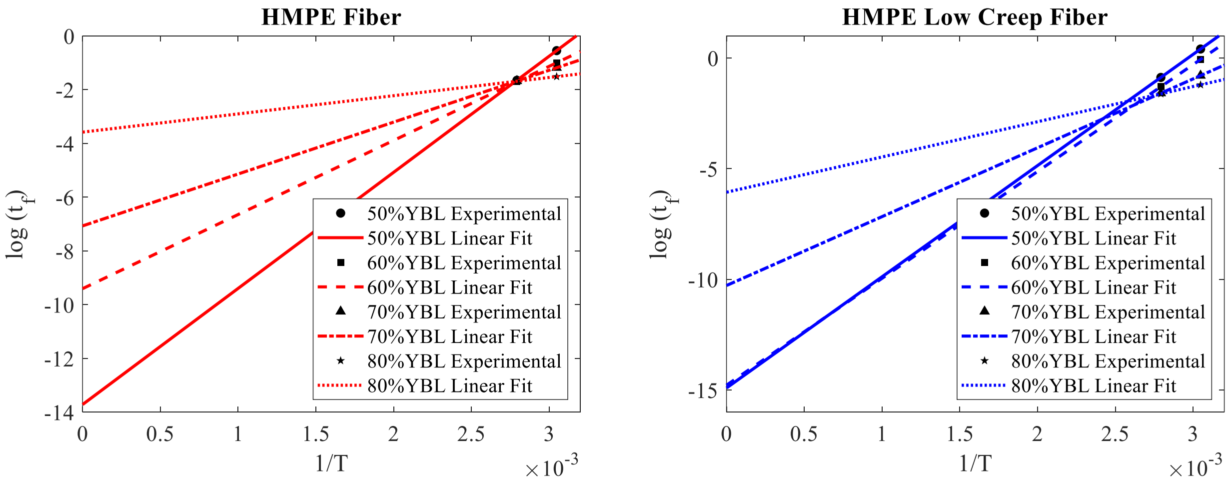


Figure 5. **Graphical construction of the material parameter C for each load condition, HMPE on the left and HMPE low creep on the right.**

The points of intersection of the fits with the y-axis represent the material's parameter C in absolute value. Table 4 presents the values obtained from the experimental data. It should be noted that this parameter's independence concerning temperature, it's solely a function of the load.

Table 4. **Material parameter C obtained in each condition in the independent term of linear adjustments.**

Load Condition [%YBL]	HMPE	HMPE Low Creep
50	13.7157	14.9075
60	9.4046	14.7815
70	7.0689	10.2774
80	3.5797	6.0624

With the material parameter determined, Eq. (2) is used to determine the Larson-Miller parameter (LMP). Table 5 presents all the values for the LMP parameter for all load and temperature conditions for the HMPE fiber. Similarly, Tab. 6 presents the LMP parameters for the low creep HMPE fiber. It is noted in both tables that the values coincide for the same temperature condition, indicating that it is a parameter dependent solely on the load.

Table 5. **Larson-Miller Parameter LMP for each condition load-temperature, HMPE fiber.**

Load Condition [%YBL]	Temperature [°C]	LMP	Mean LMP
50	55	4321.1301	4321.1299
	85	4321.1297	
60	55	2758.2305	2758.2302
	85	2758.2299	
70	55	1930.9127	1930.9122
	85	1930.9117	
80	55	677.8456	677.8454
	85	677.8452	

Table 6. **Larson-Miller Parameter LMP for each condition load-temperature, HMPE low creep fiber.**

Load Condition [%YBL]	Temperature [°C]	LMP	Mean LMP
50	55	5025.5804	5025.5811
	85	5025.5818	
60	55	4829.5103	4829.5100
	85	4829.5096	
70	55	3112.1553	3112.1559
	85	3112.1565	
80	55	1592.5369	1592.5369
	85	1592.5370	

If we examine the terms of Eq. (2), both parameters (C and LMP) have been determined, resulting in an expression in terms of creep failure time and temperature. Upon reviewing the results for both parameters, it is evident that they depend on the creep load. If the objective is to model creep life, the goal is to determine the final rupture time t_f, by isolating it in the same equation and expressing it as a function of load and temperature. To handle parameter variations, linear adjustments can be adopted for C and LMP as functions of the load.

For the HMPE fiber, linear adjustments are made based on the data obtained for each parameter, graphically depicted with equations in Fig. 6. Similarly, Fig. 7 illustrates the same for the low creep HMPE fiber.

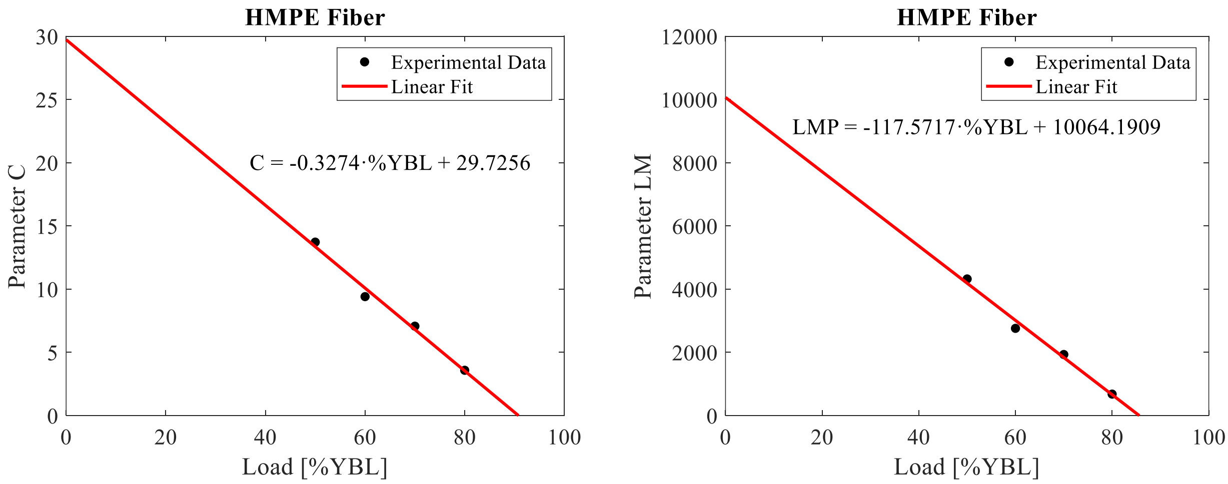
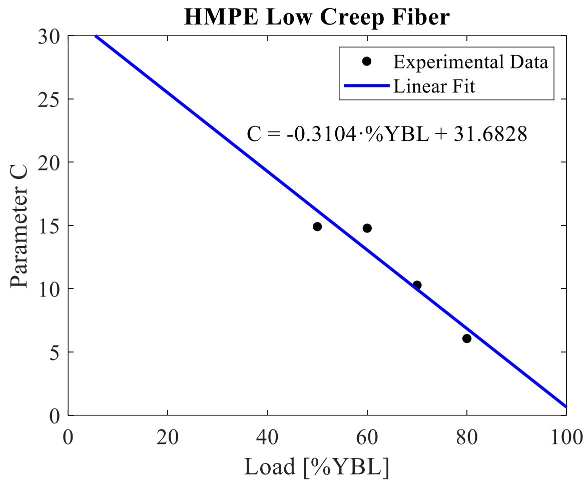


Figure 6. **Linear fit for C (left) and LM (right) parameters, HMPE fiber.**



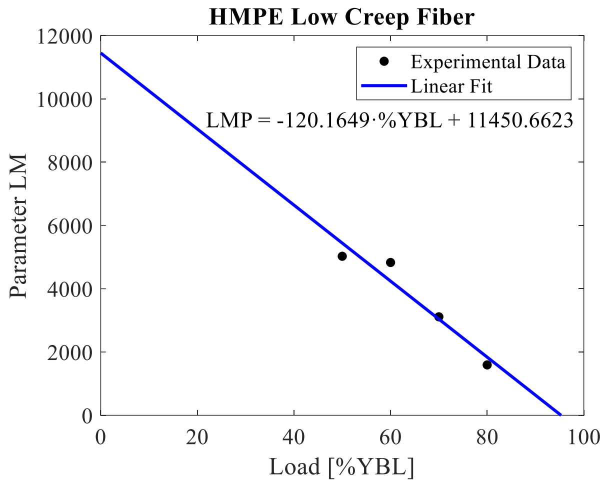


Figure 7. **Linear fit for C (left) and LM (right) parameters, HMPE low creep fiber.**

Once the expressions for parameter adjustments are obtained, Eq. (2) can be rearranged to isolate t_f, as shown Eq. (3).

$$t_f = 10^{\left(\frac{LMP}{T} - C\right)} \tag{3}$$

For each fiber, the linear adjustments of the parameters as a function of %YBL can be inserted into the expression, resulting in a final equation in terms of load and temperature. Equation (4) is proposed for the HMPE fiber, and Eq. (5) for the low creep (LC) HMPE fiber.

$$t_f = 10^{\left(\frac{(-117.5717\times\%YBL+10064.1909)}{T} - (-0.3274\times\%YBL+29.7256)\right)} \tag{4}$$

$$t_{f_{LC}} = 10^{\left(\frac{(-120.1649\times\%YBL+11450.6623)}{T} - (-0.3104\times\%YBL+31.6828)\right)} \tag{5}$$

These equations can provide indications of creep life for arbitrary load and temperature conditions. The critical aspect of the obtained equation is that ideally, a wide range of load and temperature conditions should be explored to formulate the model. However, due to the good fits obtained, it at least ensures reliable performance within the interpolation of the load and temperature groups addressed in this study.

Although modeled at a multifilament level, it becomes interesting to observe through the obtained model the life expectancy under creep, and the difference between HMPE fiber and low creep HMPE fiber. Adopting the arbitrary values of 20% of the YBL (usually maximum working load is close to this percentage), and a temperature of 16°C, or 289.15K (average temperature in shallow oceanic waters), one can obtain through Eq. (4) and Eq. (5) the predictions of creep life in hours for HMPE fiber and low creep HMPE fiber, respectively.

For HMPE fiber, values in the order of 3 thousand hours are obtained for lifetime in creep, as shown in Eq. (6). For low creep (LC) HMPE fiber, values in the order of 650 thousand hours are obtained (216 times greater than that of conventional HMPE fiber), Eq. (7).

$$t_f = 10^{(3.4890)} \cong 3083\ [h] \cong 128\ [day] \cong 0.35\ [year] \tag{6}$$

$$t_{f_{LC}} = 10^{(5.8144)} \cong 652228\ [h] \cong 27176[day] \cong 74.45\ [year] \tag{7}$$

The time to creep resistance is significantly different for conventional and low creep HMPE fibers. For this reason, entire permanent mooring systems made of HMPE are prospected and studied for low creep fibers, such as DM20, SK75, SK78, and more recently Chinese low creep fibers (addressed in this study), which demonstrate mooring longevity surpassing the operational life of the installation (≈ 25 years).

Nevertheless, for conventional HMPE fiber, the result is numerically attention-grabbing, with a lifetime less than one year. It should be noted that the structure of offshore mooring ropes is different: various construction levels, braids and twists, braid pitch, coating bath, eye splice, jacket. In this study, experiments are conducted at a basic multifilament/yarns level, which alters this correlation between different levels. Future studies should address this correlation, so that a lower construction level can represent superior construction levels through adjustments. But the results are consolidated regarding the proportions of creep resistance for conventional and low creep HMPE fibers.

4. CONCLUSIONS

Conclusions can be divided into two aspects: the experimental and the lifetime in creep model.

For the experimental data obtained, it is evident from the creep rupture curves the superior behavior of low creep HMPE fiber, enduring significantly longer times, even for applications at high temperatures (55°C and 85°C). The experimental data infer that as the temperature decreases, the low creep fiber further enhances its creep behavior compared to normal HMPE fiber.

Regarding the results of the life in creep modeling, while the model is not overly complex for its determinations, it also appears somewhat incipient, since ideally, for a general model with reliability in predicting creep life, it should be constructed with experimental data under more temperature and load conditions. Nevertheless, a model with good curve fittings was obtained (at least for the intervals studied).

It is noteworthy to highlight the creep life prediction values made with the models obtained for loads and temperatures close to real usage conditions (20%YBL and 16°C). Under these conditions, the low creep HMPE fiber exhibited a creep life behavior more than 216 times greater than normal HMPE fiber.

Furthermore, it should be emphasized that these are Chinese-manufactured materials, with a lower specific price compared to other fibers in the market. This low creep fiber has shown very promising results, with behavior like fibers manufactured in Europe, which have a much higher price.

The research lays the groundwork for numerous future investigations and studies. There is also potential for progressive development, transitioning from multifilaments to strands or sub-ropes. Moreover, there is an opportunity to explore a wider range of temperatures and loads to establish a more dependable and versatile model applicable to diverse conditions.

5. ACKNOWLEDGEMENTS

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